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# Photometric Solutions of Three Eclipsing Binary Stars Observed from Dome A, Antarctica

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## Abstract

Based on spectroscopic observations for the eclipsing binaries CSTAR 036162 and CSTAR 055495 with the WiFeS/2.3 m telescope at SSO and CSTAR 057775 with the Mage/Magellan I at LCO in 2017, stellar parameters are derived. More than 100 nights of almost-continuous light curves reduced from the time-series photometric observations by CSTAR at Dome A of Antarctic in $i$ in 2008 and in $g$ and $r$ in 2009, respectively, are applied to find photometric solutions for the three binaries with the Wilson–Devinney code. The results show that CSTAR 036162 is a detached configuration with the mass ratio $q = 0.354 \pm 0.0009$, while CSTAR 055495 is a semi-detached binary system with the unusual $q = 0.946 \pm 0.0006$, which indicates that CSTAR 055495 may be a rare binary system with mass ratio close to one and the secondary component filling its Roche Lobe. This implies that a mass-ratio reversal has just occurred and CSTAR 055495 is in a rapid mass-transfer stage. Finally, CSTAR 057775 is believed to be an A-type W UMa binary with $q = 0.301 \pm 0.0008$ and a fill-out factor of $f = 0.742(8)$.

*Key words:* binaries: eclipsing – stars: individual (CSTAR 036162, CSTAR 055495, CSTAR 057775)

*Supporting material:* data behind figures

## 1. Introduction

High-quality photometric and spectroscopic observations for eclipsing binary stars could provide good opportunities for one to derive the stellar parameters, such as masses, radii, and effective temperatures of the component stars and to investigate the star formation and chemical evolution histories (Torres et al. 2010; Feiden 2015).

Based on the Roche lobe configurations, eclipsing binaries can be classified as three types (Alcock et al. 1997): detached, semi-detached, and contact. Some authors indicated that a detached binary can evolve to be a semi-detached binary followed by a contact binary (Iben 1991; Tutukov et al. 2004; Yakut & Eggleton 2005; Stępień & Gazeas 2012). For binary systems, although the evolution toward contact binaries has been confirmed, the evolution during and beyond the contact phase is not well identified due to the lack of observation data (Stępień & Gazeas 2012). The evolutionary paths transform cool contact binaries (i.e., W UMa type binaries) to two subtypes: A-type and W-type. The evolutionary paths of the two subtypes are similar, whereas the different mass/energy transfer rates modify their physical parameters, influence their evolutions and lead to different results (Gazeas & Stępień 2008). Using the light curves and the radial-velocity curves of W UMa type binaries, an alternative evolutionary scenario was presented by Binnendijk (1970). In an A-type binary, the more massive component is hotter; whereas in a W-type binary, the secondary less massive component is hotter. The spectral types of A- and W-type systems range from A to G and F to K, respectively, but a significant overlap is present (Hilditch et al. 1988). The A- and W-type binaries differ substantially in mass ratio, and the temperature difference is usually a few hundred kelvin (Smith 1984), whereas, for some binaries, the temperature difference may be close to zero or even sometimes alternating between A- and W-type. At present, it is unconfirmed whether the division of A- and W-type is superficial or fundamental (Gazeas & Stępień 2008). In this case, more observations of eclipsing binaries at some special phases are expected.

Long, continuous, and multi-color time-series photometric observations may lead to significant insights into the astrophysical properties and evolutionary states for each component of eclipsing binary stars. Due to the unparalleled advantages of observational conditions (e.g., the high altitude, low temperature, low absolute humidity, low wind, and extremely stable atmosphere), Dome A of the Antarctic plateau is deemed as one of the best astronomical observing sites on the Earth for long-term near-continuous time-series observations (Saunders et al. 2009; Wang et al. 2011, 2017). The Chinese Small Telescope ARray (CSTAR) was deployed at Dome A (77°21′ east, 80°22′ south, 4093 m elevation) and made observations during the winters of 2008–2011. CSTAR consists of four 14.5 cm optical Schmidt-Cassegrain telescopes, each of which has a field of view of 4°.5 × 4°.5 with different ($g$, $r$, $i$ and open) Sloan filters (Frei et al. 1996; Zhou et al. 2010). Fifty-three eclipsing binaries among more than 260 variable stars have been detected from the three-year observations (Yang et al. 2015). Three stars, CSTAR 036162, CSTAR 055495, and CSTAR 057775, are found to have

**Table 1**
Parameters of the Three Eclipsing Binary Systems

| Objects | CSTAR 036162 | CSTAR 055495 | CSTAR 057775 |
|---|---|---|---|
| R.A. | $09^h03^m59^s.287$[a] | $07^h43^m54^s.49$[b] | $06^h40^m47^s.150$[c] |
| Decl. | −88°33′07 61″[a] | −89°07′37 3″[b] | −88°15′21 34″[c] |
| 2MASS ID | 09035917–8833075 | 07435276–8907369 | 06404718–8815211 |
| ASAS ID | 090354–8833.1 | 074400–8815.4 | 064047–8815.4 |
| GSC 2.3 ID | S3YB000243 | S3Y8000078 | S3YA000492 |
| Tycho-2 ID | TYC 9518–443-1 | ⋯ | TYC 9505–187-1 |
| *i* (mag) | 11.327 | 12.456 | 11.580 |
| *r*, *g* (mag) | 11.66, 11.80 | 12.68, 13.08 | 11.93, 12.08 |
| *J*, *H*, *K* (mag) | 10.540, 10.309, 10.230 | 11.443, 11.500, 11.418 | 10.717, 10.451, 11.82 |
| *V* (mag) | 11.53 | 12.594 | 11.82 |
| *B* (mag) | 12.19 | ⋯ | 12.63 |
| Period (days) | 0.873857 | 0.798017 | 0.438659 |
| Amplitude *V* (mag) | 0.29 | 0.65 | 0.45 |
| $\mu_\alpha$, $\mu_\delta$ (mas $yr^{-1}$) | 1.5, −3.4 | 0.8, 5.0 | 5.8, −1.0 |

**Notes.**
[a] Data source: Skrutskie et al. (2006).
[b] Data source: Wang et al. (2011).
[c] Data source: Pojmanski (2003).
The row descriptions are as follows: Header: CSTAR identifier (Wang et al. 2011). Rows 1 and 2: $\alpha_{2000}$ and $\delta_{2000}$ from SIMBAD. Row 3: 2Mass identifier (Skrutskie et al. 2006). Row 4: ASAS identifier (Pojmanski 2003). Row 5: GSC identifier (Samus et al. 1997). Row 6: Tycho-2 identifier (Høg et al. 2000) Row 7: Median apparent magnitude in the *i* band (Wang et al. 2011). Row 8: magnitude in the *r* and *g* bands (Oelkers et al. 2015). Rows 9: *JHK* near-infrared magnitude from the 2MASS catalog (Skrutskie et al. 2006). Row 10: Johnson V magnitude from the ASAS catalog (Pojmanski 2003). Row 11: Johnson B magnitude from the GCVS (Høg et al. 2000). Row 12: Period of the eclipsing binaries (Wang et al. 2011). Row 13: Amplitude in *V* band (Pojmanski 2003). Row 14: Proper motions in right ascension and declination from the PPMXL catalog (Roeser et al. 2010).

relatively high precision and long duration coverage data in three filters, and they receive top priority to be analyzed among these eclipsing binary stars.

The three eclipsing binary stars CSTAR 036162, CSTAR 055495, and CSTAR 057775 were observed by CSTAR during the winters of 2008, 2009, and 2010 (Zou et al. 2010; Wang et al. 2011, 2013, 2014; Oelkers et al. 2015; Zong et al. 2015). Following Wang et al. (2011),[9] we adopted the IDs of the three eclipsing binary stars, which are identified as variable stars by the General Catalog of Variable Stars (GCVS; Samus et al. 1997), All-sky Automated Survey (ASAS; Pojmanski 2002), and Two Micron All-sky Survey (2MASS; Skrutskie et al. 2006) as well.

Photometric light curves of the three binaries in the *i* band were collected by CSTAR in 2008 and extracted by Wang et al. (2011). With the light curves, Yang et al. (2015) provided the orbital parameters, including the temperature ratio ($T_2/T_1$), eccentricity ($e$), and sine of inclination ($\sin i$) of the systems by using the Eclipsing Binaries via Articial Intelligence method (EBAI; automated modeling, Devinney et al. 2005, 2006). The results indicate that CSTAR 036162 and CSTAR 055495 are semi-detached systems while CSTAR 057775 is a contact system. The fundamental parameters of the three binaries are listed in Table 1. The bi-color photometric observations of the three binaries were performed by CSTAR in the winter of 2009. The light curves had been extracted by Zong et al. (2015) and Oelkers et al. (2015). Based on the long-term light curves in the *i*, *g*, and *r* bands in 2008 and 2009 and the spectroscopic observations carried out in 2016 and 2017, we aim to find more precise solutions of the geometrical configurations and evolutionary stages of the three binaries. This paper consists of six sections. The observations and data reduction are presented in Section 2. The new linear ephemeris is presented in Section 3. Synthetic light curves and geometric parameters of the three binaries are provided in Section 4. Comparison of parameters derived from this work and previous work, together with the discussion, are presented in Section 5. Section 6 presents the conclusions.

## 2. Observations and Data Reduction

Time-series photometric observations in the *i*, *g*, and *r* bands of CSTAR 036162, CSTAR 055495, and CSTAR 057775 were made with CSTAR during the winters of 2008 and 2009. In the winter of 2008, the telescopes equipped with the *g*, *r* and "open" filters had technical problems and obtained no useful data (Wang et al. 2011). Fortunately, the telescope equipped with the *i* filter ran with no issues. In the winter of 2009, observations in the *g* and *r* bands were made continuously. Figure 1 shows a sample image in the *r* band of the three objects observed by CSTAR on 2009 June 23 with the exposure time of 20 s. The preliminary reduction of the raw images includes bias subtraction, flat-fielding and fringe correction (Zhou et al. 2010; Wang et al. 2011; Zong et al. 2015). The DAOFIND program of the IRAF[10] (Tody 1986, 1993) package was used to identify stars on each image; While DAOPHOT and ALLSTAR were used to perform synthetic aperture photometry for the stars (Stetson 1987). The magnitude calibration was made based on the *Tycho* catalog (Ofek 2008). The log of the observation data of the three

[9] Note: Wang et al. (2013) updated the IDs in their catalog. The three stars here, CSTAR 036162, CSTAR 055495, and CSTAR 057775 are identified as n059543, n083359, and n086263, respectively.

[10] Image Reduction and Analysis Facility (IRAF) is a software system for the reduction and analysis of astronomical data. It is written and supported by the National Optical Astronomy Observatories (NOAO) and can be found at http://iraf.noao.edu/.

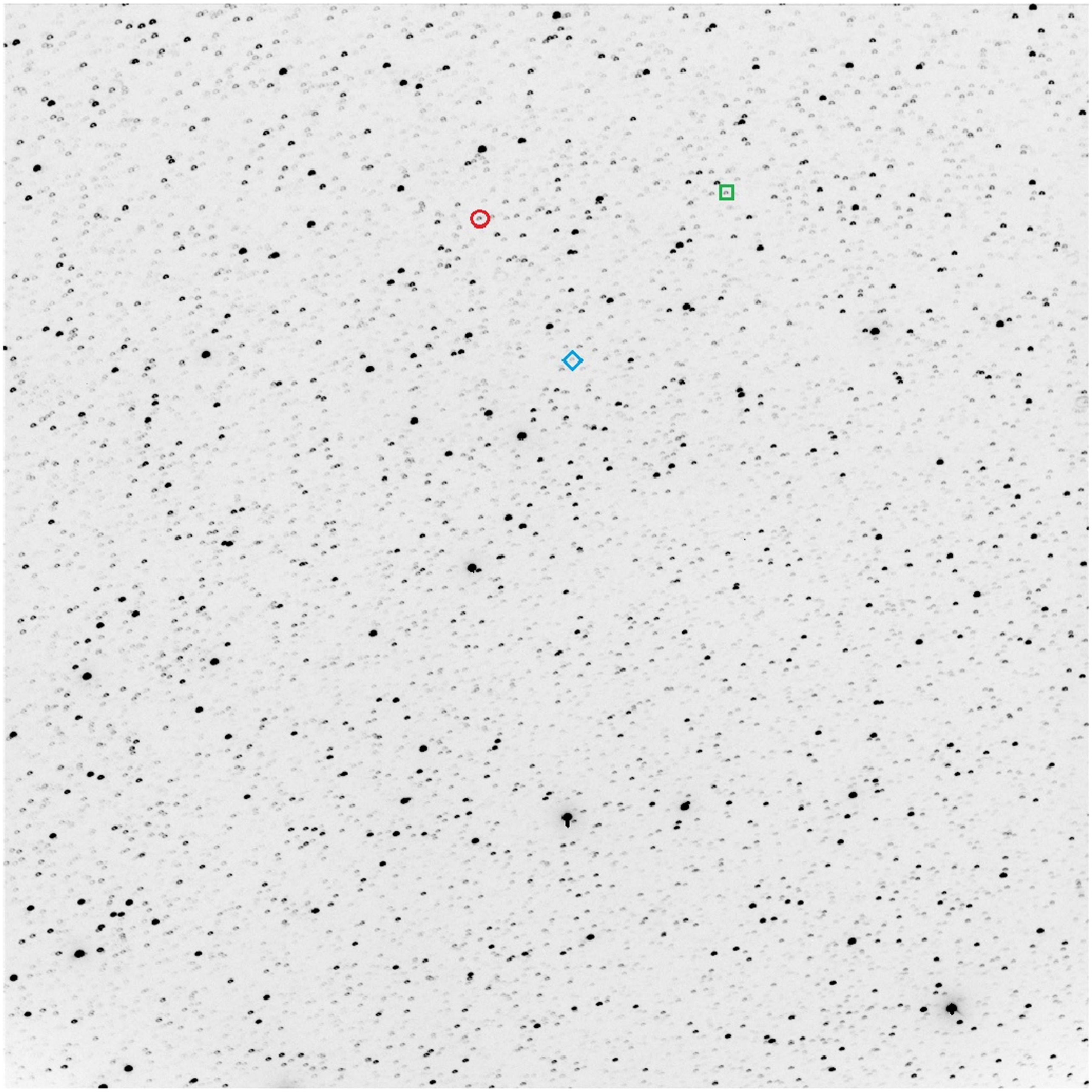

**Figure 1.** A CCD image with CSTAR 036162 (red circles), CSTAR 055495 (blue diamond) and CSTAR 057775 (green rectangle) observed by CSTAR in the $r$ band. The field of view is 4°.5 × 4°.5, centered to the south celestial pole (decl. = 90°). The image was taken on 2009 June 23 with the exposure time of 20 s.

**Table 2**
Log of CCD Photometric Observations of the Three Binaries in the $i$ Band in 2008, in the $g$ and $r$ Bands in 2009

| Name | Filter | Frame | Integral Time (hr) | Mag (mag) | Error (mag) |
|---|---|---|---|---|---|
| | $i$ | 131260 | 741.8 | 11.42 | 0.02 |
| CSTAR 036162 | $r$ | 216638 | 1203.5 | 11.57 | 0.02 |
| | $g$ | 99794 | 554.4 | 11.91 | 0.04 |
| | $i$ | 130374 | 741.3 | 12.55 | 0.04 |
| CSTAR 055495 | $r$ | 216063 | 1200.4 | 12.85 | 0.09 |
| | $g$ | 93597 | 520.0 | 13.32 | 0.13 |
| | $i$ | 131897 | 750.3 | 11.74 | 0.02 |
| CSTAR 057775 | $r$ | 222280 | 1234.9 | 11.88 | 0.03 |
| | $g$ | 94158 | 523.1 | 12.25 | 0.07 |

binaries is listed in Table 2. Using the color index $g - r$ in 2009 and Equation (23) of Fukugita et al. (1996), magnitude transformation from the SLOAN system to the Johnson–Morgan–Cousins system $(B - V)$ is performed. The temperature of the primary star is estimated by using the empirical formula: $T_{\rm eff} = 8540/[(B - V) + 0.865]$ $(4000 < T < 10{,}000)$. The effective temperatures of CSTAR 036162, CSTAR 055495, and CSTAR 057775 are derived as $6060 \pm 330$ K, $5564 \pm 900$ K and $5960 \pm 520$ K, respectively.

Spectroscopic observations of CSTAR 036162 and CSTAR 055495 were carried out in 2016 with the 2.3 m telescope at the Siding Spring Observatory (SSO), Research School of Astronomy and Astrophysics (RSAA) of the Australian National University (ANU). The telescope was equipped with the Wide-field Spectrograph (WiFeS; Dopita

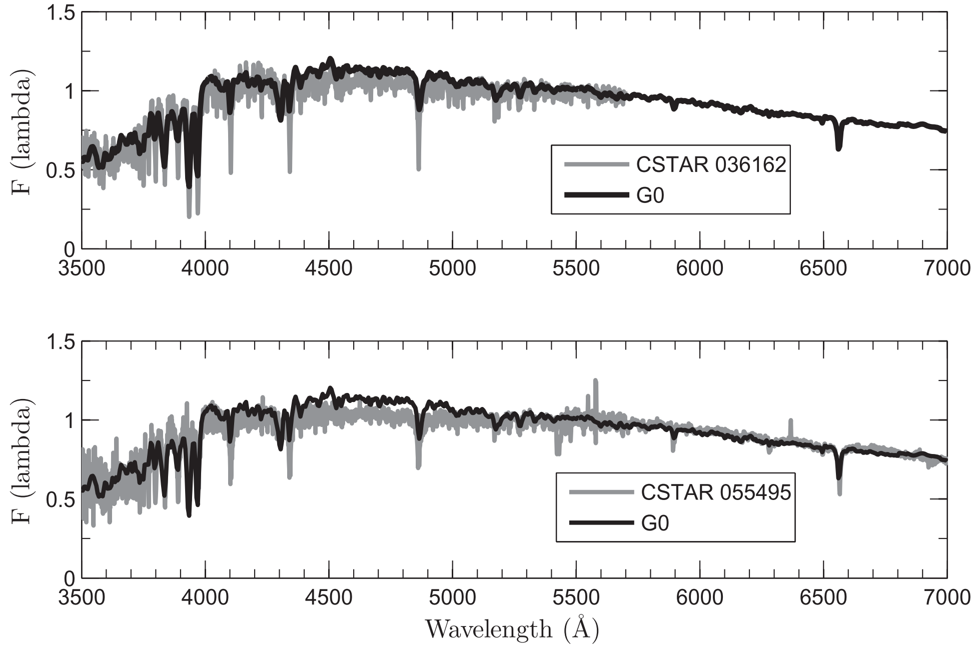


**Figure 2.** Top panel: spectrum of CSTAR 036162 (the black solid line) observed with the WiFeS/2.3 m telescope at SSO in Australia. The gray solid line refers to the spectrum of a G0 star in the library (Pickles 1998). Bottom panel: spectrum of CSTAR 055495 and a G0 star.

et al. 2007, 2010) and 4096 × 4096 Fairchild Imaging CCDs. The wavelength range extended from 350 to 570 nm in blue arm and from 540 to 700 nm in red arm, respectively. The spectral resolution was 3000 (Dopita et al. 2010). A detailed reduction procedure is performed with PyWiFeS[11] which is a newly-developed Python-based data reduction pipeline for the WiFeS (Childress et al. 2014). The reduction procedure includes: image pre-processing (e.g., overscan subtraction, bias subtraction, slitlets separation, cosmic ray rejection, flat correction, scattered light accounting), "data cube" generating from the raw WiFeS CCD frames, flux, and wavelength calibration, and blue and red band spectrum stitching.

The spectroscopic observation of CSTAR 036162 was made on 2016 October 15 with the exposure time of 120 s. After data reduction, the obtained spectrum is shown in the top panel of Figure 2. After comparing with the spectrum flow library presented by Pickles (1998), the spectral type of CSTAR 036162 is preliminarily identified as G0. The low-resolution optical spectrum of CSTAR 055495 was obtained on 2016 August 29 with the exposure time of 180 s. The reduced spectrum is shown in the bottom panel of Figure 2. After comparing with the spectrum flow library, the spectral type of the primary star of CSTAR 055495 is preliminarily identified as G0. Based on the spectra, the effective temperatures of the primary stars are derived as 5848 K and 5848 K for CSTAR 036162 and CSTAR 055495, respectively. Both values are in agreement with temperatures derived from the color indices within the uncertainties.

The spectroscopic observations of CSTAR 057775 were made by using the Magellan Echellette Spectrograph (MagE; Marshall et al. 2008), a moderate-resolution optical echellette of the 6.5 m Magellan I telescope at Las Campanas Observatory (LCO) in Chile, during the night of 2017 September 07 with the exposure time of 350 s. The slit was 10 arcsec long with a plate scale of 0.3 arcsec/pixel on the detector and the spectral coverage spans roughly from 320 to 1000 nm.

The data were reduced using a combination of the "mtools" package[12] and usual IRAF echelle routines, following standard procedures for bias correction, flat-fielding, wavelength calibration, and order stitching. We use the ULySS package[13] (Koleva et al. 2009) to determine the stellar atmospheric parameters as $T_{\rm eff} = 6397 \pm 5$ K, $\log g = 3.788 \pm 13$ and $[{\rm Fe/H}] = -0.0175 \pm 0.008$ and derive the spectral type of the primary star as F6 V. The temperature value from the spectrum is in agreement with that determined from the color indices within the uncertainties. The spectrum of CSTAR 057775 is shown in Figure 3.

## 3. Linear Ephemeris

A total of 121 occurrences (34 in the *i* band, 33 in the *g* band, and 54 in the *r* band) of minimum light of CSTAR 036162 are derived via parabolic fitting. The errors are estimated with the Monte Carlo method. Based on these data, the linear ephemeris is calculated as,

$$\text{CSTAR 036162 : Min.}I = HJD\ 2454571.34300(8) + 0\overset{\rm d}{.}873777(1) \times E, \quad (1)$$

where the errors are shown in the parentheses. $T_0 = HJD2454571.34300$ is the time of a primary eclipse. Min $I$ means the primary eclipse time. HJD refers to the heliocentric Julian date. $E$ is the cycle number.

[11] http://www.mso.anu.edu.au/pywifes/doku.php?id=start

[12] The IRAF "mtools" package was written by Jack Baldwin for dealing with the tilted slits in MIKE spectra. This package can be found at http://www.lco.cl/telescopes-information/magellan/instruments/mike/idl-tools/iraf-mtools-package.

[13] ULySS (University of Lyon Spectroscopic analysis Software) is an open-source software package written in the GDL/IDL language to analyze astronomical data. It fits a spectrum with a linear combination of nonlinear components convolved with a line-of-sight velocity distribution (LOSVD) and multiplied by a polynomial continuum. This package can be found at http://ulyss.univ-lyon1.fr/.

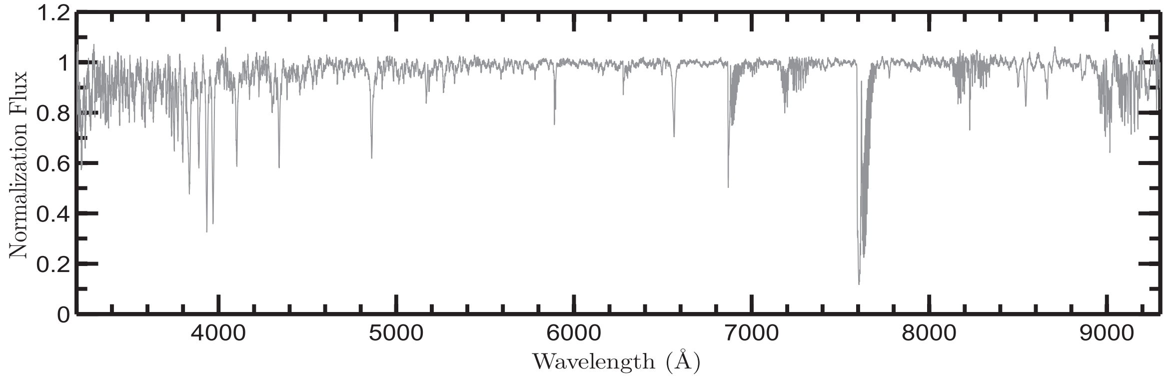


**Figure 3.** Normalized spectrum of CSTAR 057775 observed with the Mage/Megallen I at LCO in Chile. The spectral type of the primary component is estimated as F6 from the stellar spectral model of ULySS.

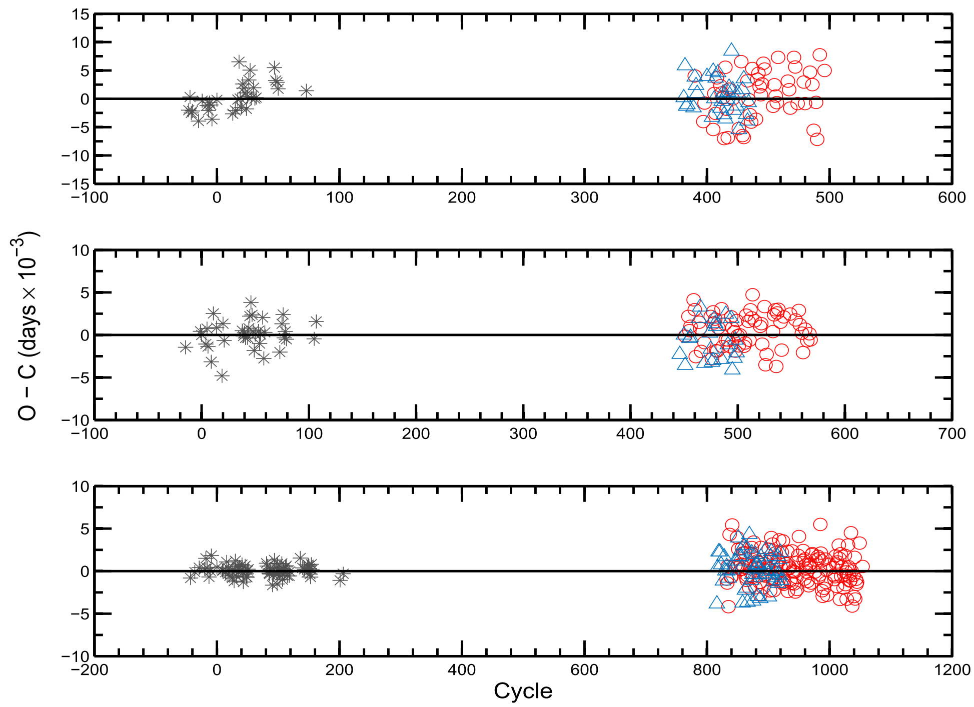


**Figure 4.** O − C diagrams of CSTAR 036162 (top), CSTAR 055495 (middle), and CSTAR 057775 (bottom), respectively. The gray star symbols refer to the light minima in the *i* band in 2008, while the blue triangles and red cycles for those in the *g* and *r* bands in 2009, respectively. The black solid lines are the fitting straight lines.

For CSTAR 055495, 38 times of primary eclipse in the *i* band, 68 in the *r* band, and 24 in the *g* band are determined. The linear ephemeris is derived as,

$$\text{CSTAR 055495} : \text{Min.}I = HJD\ 2454584.43917(9) + 0\overset{\text{d}}{.}798004(6) \times E. \quad (2)$$

For CSTAR 057775, 77 times of primary eclipse in the *i* band, 157 in the *r* band, and 93 in the *g* band are obtained. A linear fit leads to,

$$\text{CSTAR 057775} : \text{Min.}I = HJD\ 2454580.16095(8) + 0\overset{\text{d}}{.}4386203(1) \times E. \quad (3)$$

The Observed − Calculated (hereafter, O − C) diagrams of the three binary systems are shown in Figure 4. The data can be clearly divided into two groups in time due to a gap of observation. The linear solid lines show the straight line fits.

## 4. Photometric Solutions

For the three binaries, the photometric observations in the *i* band in 2008, along with those in the *g* and *r* bands in 2009, are used to deduce the photometric solutions with the Wilson–Devinney (W–D) code[14] (Wilson 1971, 1979, 1990, 2012) and the Kurucz atmosphere model (Kallrath et al. 1998). The effective temperatures of the primary star of CSTAR 036162, CSTAR 055495, and CSTAR 057775 are derived from the spectra. The light curves of the binaries are averaged to 2000 points in each band. $g_1$ and $g_2$ as the input parameters of the

[14] The W–D code was developed by Robert E. Wilson (University of Florida) and used to compute light curves for eclipsing binaries. It consists of a main Fortran program (LC) for generating light and radial-velocity curves, spectral line profiles, and images, plus a differential corrections main program (DC) for parameter adjustment of light and velocity curves by the Least Squares criterion, and about three dozen subroutines used by both main programs. In this work, we use the 2013 version of the W–D code, which can be found at ftp://ftp.astro.ufl.edu/pub/wilson/.

W–D mode refer to the exponents in the bolometric gravity darkening law for the two components, respectively. For the convective envelopes of late-type stars, $g_1$ and $g_2$ are generally taken as $4 \times \beta = 0.32$ ($\beta = 0.08$; Lucy 1967; Rovithis & Rovithis-Livaniou 2007). The input parameters $A_1$ and $A_2$ refer to the bolometric albedos for reflection heating and re-radiation on the two components, respectively. The bolometric albedo is the local ratio of the re-radiated bolometric energy to receive bolometric energy. For convective envelopes, it is taken as 0.5 (Ruciński 1969). The parameters $X_1$, $X_2$, $Y_1$, and $Y_2$ refer to the coefficients in the bolometric limb-darkening law (van Hamme 1993). They are used in the computation of reflection in detail. Alencar & Vaz (1999) indicated that better results could be obtained by using a logarithmic law for cooler stars, so in this paper, we use the logarithmic law. The parameters $x_{1\text{band}}$, $y_{1\text{band}}$, $x_{2\text{band}}$ and $y_{2\text{band}}$ refer to the wavelength-specific limb-darkening coefficients. We also use the logarithmic law to calculate these four parameters (Claret 2004). The limb-darkening effect is analyzed by using the method of Qian et al. (2015). First, we set the values of the corresponding coefficients of the two components ($X_1 = X_2$, $Y_1 = Y_2$, $x_{1i} = x_{2i}$, and $y_{1i} = y_{2i}$) according to the effective temperatures of the primary components. Then, we derive the actual effective temperatures of the secondary stars. The values of the bolometric and limb-darkening coefficients of the secondary stars are redetermined based on the actual temperatures. At last, the values of the convergence parameters are obtained by using the W–D program.

As no radial-velocity curves are obtained for the three binaries, the photometric solutions are tested by adopting the assumed mass ratios of $q = 0.1$–$3.0$ with the interval step of 0.1 to look for the most probable mass-ratio values. With the assumed $q$ values, we run the Differential Corrections main program (hereafter, DC) of the W–D code from mode 2 (detached configuration). After several iterations, the converged solutions are reached. Figure 5 shows the residuals between the synthetic and observed light curves versus the $q$ values, where the most probable $q$ values are obtained at the minimum residual values. We run the DC program again with the most probable $q$ values and adjust the parameters freely, which include the $q$ values, the temperatures of the secondary star ($T_2$), the orbital inclinations ($i$), the surface potentials of both components ($\Omega_1$ and $\Omega_2$), and the monochromatic luminosities of the primary star ($L_1$). The best-fitting solutions are obtained and listed in Table 3. Based on the solutions in this table, the syntheses of the observed light curves of the three binaries are shown in Figures 6–8, respectively. The results show that: (1) CSTAR 036162 has a detached configuration; (2) CSTAR 055495 has a semi-detached configuration with the secondary companion filling its Roche lobe, and (3) CSTAR 057775 has a contact configuration ($\Omega_1 = \Omega_2$).

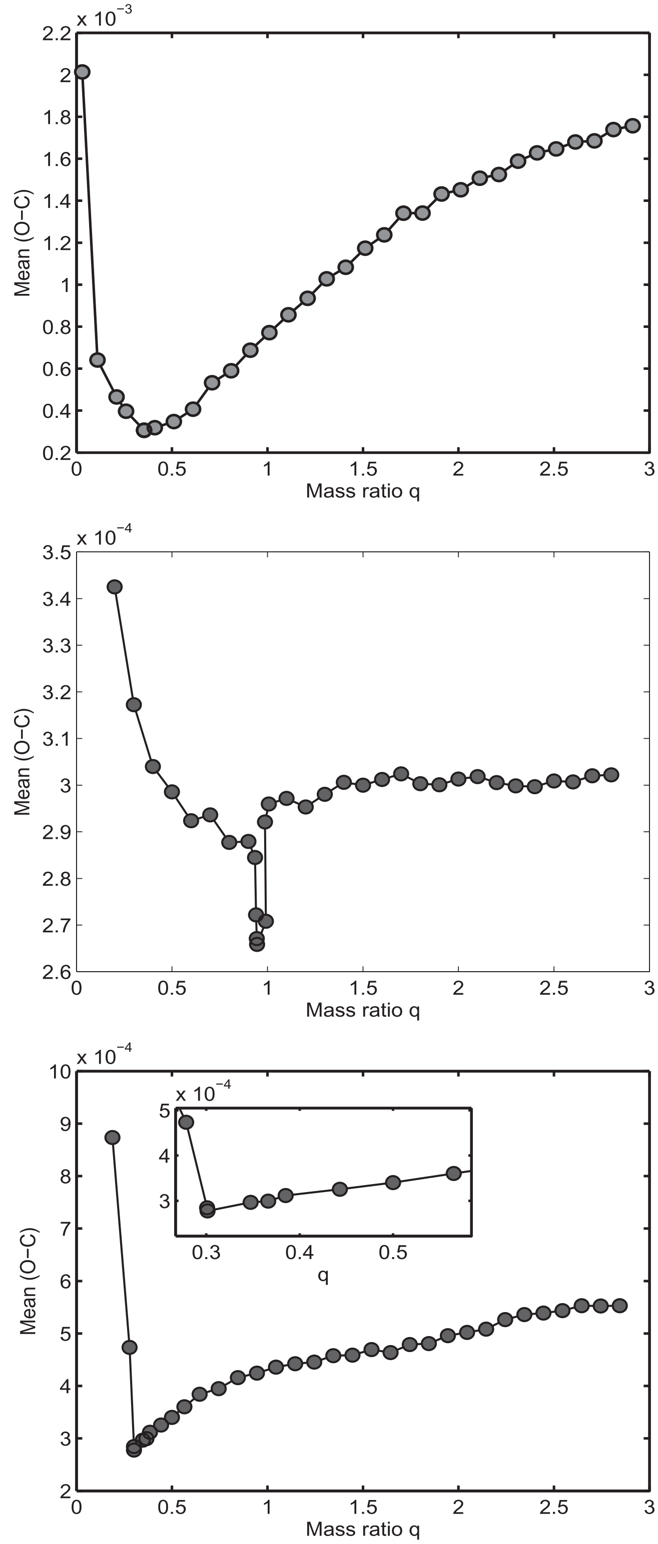


**Figure 5.** The $q$-search diagram of CSTAR 036162 (top), CSTAR 055495 (middle), and CSTAR 057775 (bottom), respectively.

## 5. Discussion

### 5.1. CSTAR 036162

A total of 121 times of minimum light of CSTAR 036162 are determined. Based on these data, the linear ephemeris is calculated. The spectral type of the primary component is estimated as G0 with the observed spectrum. The effective temperature is determined as $T_1 = 5848$ K. With the W–D approach, we obtain the photometric solution, showing that CSTAR 036162 is a detached binary system with $q = 0.354 \pm 0.0009$. The mass of the primary component of CSTAR 036162 of $M_1 = 1.05 M_\odot$ is estimated from the empirical effective temperature-spectral type and the mass relation given by Cox (2000). The mass of the secondary component of $M_2 = 0.37 M_\odot$ is computed from the mass ratio $q = M_2/M_1$. Based on the *Kepler*'s third law: $m_1 + m_2 = (4\pi^2/G)(a^3/P^2)$ and the relative radius formula

**Table 3**
Photometric Solutions of the Three Sample Binaries

| Parameter | CSTAR 036162 | CSTAR 055495 | CSTAR 057775 |
|---|---|---|---|
| $T_1$ (K) | 5848 | 5848 | 6397 |
| $T_2$ (K) | 3820 ± 6 | 4494 ± 5 | 6327 ± 8 |
| $q = m_2/m_1$ | 0.354 ± 0.0009 | 0.946 ± 0.0006 | 0.301 ± 0.0008 |
| $i$(°) | 82.54 ± 0.04 | 68.38 ± 0.05 | 72.80 ± 0.03 |
| $\Omega_1$ | 3.151 ± 0.002 | 4.029 ± 0.01 | 2.418 ± 0.002 |
| $\Omega_2$ | 3.958 ± 0.006 | ⋯ | ⋯ |
| $L_1/(L_1 + L_2)_g$ | 0.99 ± 0.02 | 0.68 ± 0.08 | 0.77 ± 0.07 |
| $L_1/(L_1 + L_2)_r$ | 0.99 ± 0.02 | 0.76 ± 0.06 | 0.78 ± 0.04 |
| $L_1/(L_1 + L_2)_i$ | 0.98 ± 0.02 | 0.72 ± 0.06 | 0.78 ± 0.04 |
| $r_{1,\mathrm{pole}}$ | 0.3548 ± 0.0003 | 0.2622 ± 0.0006 | 0.4662 ± 0.0002 |
| $r_{1,\mathrm{point}}$ | 0.3824 ± 0.0004 | 0.2956 ± 0.0009 | ⋯ |
| $r_{1,\mathrm{side}}$ | 0.3665 ± 0.0003 | 0.2695 ± 0.0007 | 0.5041 ± 0.0002 |
| $r_{1,\mathrm{back}}$ | 0.3750 ± 0.0004 | 0.2849 ± 0.0008 | 0.5330 ± 0.0002 |
| $r_{2,\mathrm{pole}}$ | 0.1338 ± 0.0008 | 0.4114 ± 0.0013 | 0.2730 ± 0.0009 |
| $r_{2,\mathrm{point}}$ | 0.1360 ± 0.0005 | 0.5673 ± 0.0014 | ⋯ |
| $r_{2,\mathrm{side}}$ | 0.1344 ± 0.0005 | 0.4366 ± 0.0013 | 0.2860 ± 0.001 |
| $r_{2,\mathrm{back}}$ | 0.1357 ± 0.0005 | 0.4648 ± 0.0014 | 0.3286 ± 0.002 |

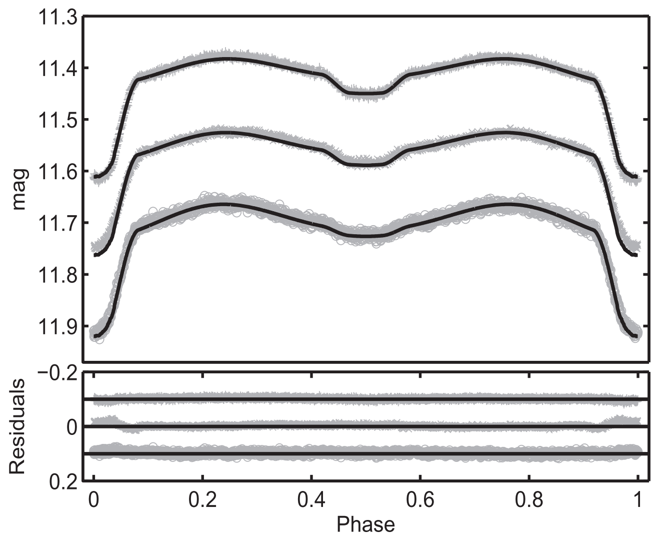


**Figure 6.** The observational and theoretical light curves of CSTAR 036162. In the upper panel, the pluses, crosses and open circles (from top to bottom) refer to the light curves in the $i$, $r$, and $g$ bands, respectively. The solid curves show the theoretical curves. In the lower panel, the corresponding residuals between the theoretical and observational light curves in the $i$, $r$, and $g$ bands are plotted from top to bottom, respectively. The data used to create this figure are available.

$r = R/a$, the radius of the components are derived from the W–D code as $R_1 = 1.58R_\odot$ and $R_2 = 0.58R_\odot$. The luminosities of the components are computed with $L = 4\pi\sigma R^2T^4$ as $L_1 = 2.62L_\odot$ and $L_2 = 0.064L_\odot$, respectively, and the spectral type of the secondary star is estimated as K4 according to its temperature.

The parameters obtained from this work and those from Yang et al. (2015) are listed in Table 4. According to the morphologies of automated classifier, CSTAR 036162 was classified as a semi-detached binary system by Yang et al. (2015). We notice the difference between the results of Yang et al. (2015) and this work. On one hand, Yang et al. (2015) used the photometric data in the $i$ band, which were obtained by CSTAR from Dome A in 2008. In this work, we use the data in three bands in both 2008 and 2009. The usage of multi-color data can better restrict the photometric solutions, as the color information in different bands is helpful to determine $T_2$. On the other hand, the goal of the EBAI project is to rapidly process large amounts of the survey data. Although the results are impressive because of the sheer number of the observed targets, the phase coverage for the individual target may be insufficient. Relative to that of the contact binaries, the main parts of the light curves of the detached binaries are in the phases out of the eclipses, and the data points in the phases in the eclipses are fewer. This may lead to larger model errors (Prša et al. 2008). Based on the *Kepler* data of 1879 eclipsing binaries, Prša et al. (2011) suggested that the manual investigation is more reliable than the automated one. According to the result with the W–D code, we believe that

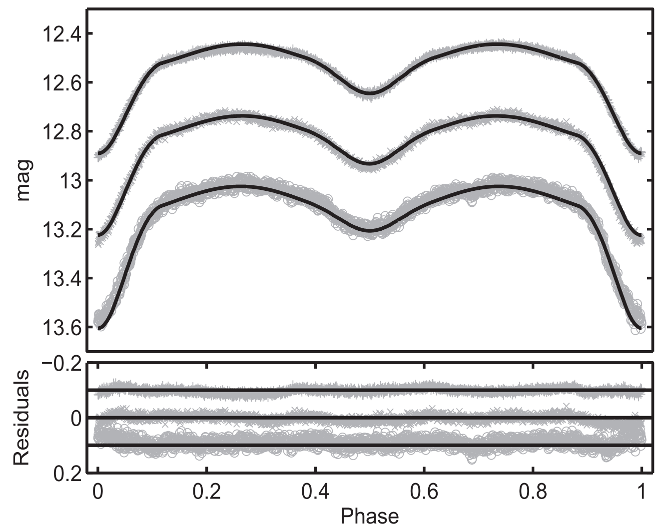


**Figure 7.** The observational and theoretical light curves of CSTAR 055495. The symbols are the same as in Figure 6. The magnitudes in the $g$ band are −0.2 mag. The data used to create this figure are available.

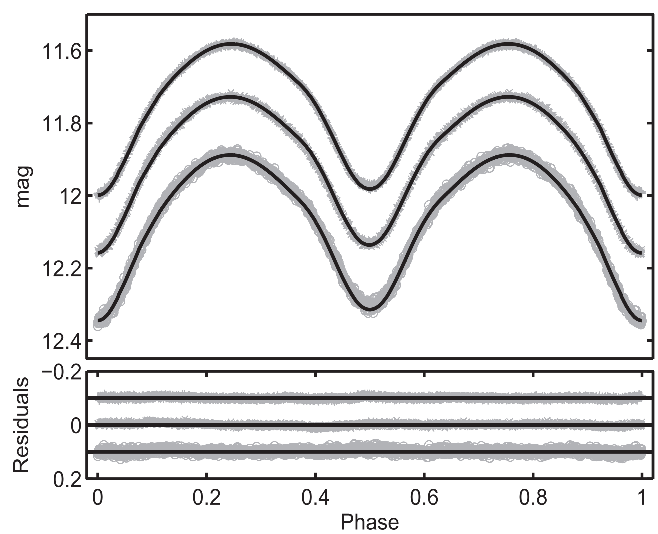


**Figure 8.** The observational and theoretical light curves of CSTAR 057775. The symbols are the same as in Figure 6. The data used to create this figure are available.

**Table 4**
Parameters Obtained from This Work Those from Yang et al. (2015)

| Objects | Code | Period (days) | $M_2/M_1$ | $T_2/T_1$ | sin $i$ | Fill-out[a] | Type |
|---|---|---|---|---|---|---|---|
| CSTAR 036162 | W–D | 0.873777(1) | 0.354 (9) | 0.653 (7) | 0.992(5) | ⋯ | D |
| | EBAI | 0.873754(2) | ⋯ | 0.596 | 0.871 | ⋯ | SD |
| CSTAR 055495 | W–D | 0.798004(6) | 0.946 (6) | 0.769(7) | 0.930(2) | ⋯ | SD |
| | EBAI | 0.797987(6) | ⋯ | 0.481 | 0.948 | ⋯ | SD |
| CSTAR 057775 | W–D | 0.4386203(1) | 0.301(8) | 0.989(2) | 0.955(9) | 0.742(8) | C |
| | EBAI | 0.438606(1) | 0.849 | 0.988 | 0.936 | 0.856 | C |

**Note.** Type D, SD, and C refer to detached, semi-detached, and contact binaries, respectively.
[a] For comparison, the formula used to calculate the fill-out fraction is consistent with Equation (1) of Yang et al. (2015).

CSTAR 036162 is a detached binary, as both $f_1$ and $f_2$ (filling factors) are negative (Equation (3.24); Prša 2006).

### 5.2. CSTAR 055495

A total of 130 occurrences of minimum light of CSTAR 055495 are obtained. Based on these data, the linear ephemeris is calculated. The spectral type of the primary component is estimated as G0 with the observed spectrum. The effective temperature is determined as 5848 K. With the W–D approach, we obtain the photometric solution, showing that CSTAR 055495 may be a rare binary system with the mass ratio close to unity and the secondary component filling its Roche Lobe.

According to the same method for CSTAR 036162, the mass of the primary component of CSTAR 055495 is estimated as $M_1 = 1.05M_\odot$. The other physical parameters are deduced as $M_2 = 0.99M_\odot$, $R_1 = 1.54R_\odot$, $R_2 = 1.74R_\odot$, $L_1 = 2.49L_\odot$, and $L_2 = 1.10L_\odot$. The derived absolute parameters indicate that the primary component could be a main-sequence star and the secondary has been already oversized relative to the main-sequence star with the same mass and filling its Roche lobe. The progenitor of CSTAR 055495 might be a detached binary. The more massive component evolves and fills its Roche lobe first; then the material transfers from the more massive star to the less massive one through the Lagrange 1. With mass transfer, the secondary component accretes material. When the two components reach the same mass, the mass-ratio reversal occurs. In this case, the secondary component, which was the more massive one, becomes a low-mass sub-giant star. This implies that CSTAR 055495 is in a rapid mass-transfer stage. If we neglect the angular momentum loss, owing to the augment of the orbit, the expansion velocity of the binary system will be slower than the increasing velocity of the Roche lobe. In this case, the mass transfer will be turned off and the contact binary will evolve to be a detached configuration (Stępień & Gazeas 2012). This semi-detached configuration with mass ratio close to one is similar to the Algol-type of FT UMa (if it is a semi-detached binary system, $q = 1.0$; Yuan 2011) and V753 Mon ($q = 1.03$; Qian et al. 2013). Semi-detached binaries with mass ratio close to unity, like CSTAR 055495, could possibly provide important insights into the formation and evolution of semi-detached binaries.

The parameters of CSTAR 055495 from this work and those from Yang et al. (2015) are listed in Table 4. From the table, one can see that parameters from the two works are different to each other, especially the $T_2/T_1$ values. We notice that Yang et al. (2015) used only observations in single $i$ band. As one knows, the $T_2/T_1$ value for detached and semi-detached configurations is not easy to be determined accurately in general. For instance, Prša et al. (2011) analyzed 1124 detached and semi-detached binaries in the *Kepler* field. Only 71% of the $T_2/T_1$ values have been determined with the uncertainties smaller than 5%, where the detached and semi-detached configurations were calculated using the neural networks. The possible reasons were described by Prša et al. (2008): if the work is based on the analysis of a single light curve, there is no inherent way to calibrate the temperatures. The authors would have to assume one of the temperatures and therefore the results suffer from systematic effects. As far as our analysis, the temperature of the primary star is derived from the observed stellar spectrum, while the calculation of the temperature of the secondary star takes into account the color indices between the three bands when running the W–D code. We therefore think that our result is more robust than the previous work. As a comparison, Kjurkchieva & Vasileva (2015) derived the orbital parameters of two binaries in the *Kepler* field with the W–D code and compared the parameters with those derived via EBAI by Slawson et al. (2011). The two results do not match each other.

### 5.3. CSTAR 057775

A total of 130 occurrences of minimum light of CSTAR 057775 are collected. Based on these data, the linear ephemeris is calculated. The spectral type of the primary component is estimated as F0 with the observed spectrum, and the effective temperature is determined as $T_1 = 6397$ K. With the W–D approach, we obtain the photometric solution, showing that CSTAR 057775 is an A-type cool contact binary with the fill-out factor of $f = 0.742(8)$ and $q = 0.301 \pm 0.0008$.

Following the same method as for CSTAR 036162, the mass of the primary component of CSTAR 057775 is estimated as $M_1 = 1.25M_\odot$, and the other physical parameters are deduced as $R_1 = 1.44R_\odot$ and $L_1 = 3.12L_\odot$. The absolute parameters of the secondary star are $M_2 = 0.38M_\odot$, $R_2 = 0.85R_\odot$, and $L_2 = 1.038L_\odot$. The parameters of CSTAR 057775 derived with the W–D method from this work and those with the EBAI method by Yang et al. (2015) are listed in Table 4. From the table, one can see that the parameters in these two works are close to each other, except for $q$. Based on the orbital period, the spectral type, the profile of light curves and $T_1 - T_2$, we believe that CSTAR 057775 is a typical A-type W UMa binary and the $q$ value from this work is more reliable than that of Yang et al. (2015).

## 6. Conclusions

We report a study of three eclipsing binaries: CSTAR 036162, CSTAR 055495, and CSTAR 057775, based on spectroscopic observations in 2016 and 2017 and multi-color time-series photometric observations from Dome A in 2008 and 2009. The geometrical configurations and the physical parameters of the three systems are derived.

1. CSTAR 036162 has a short-period detached configuration with the mass ratio $q = 0.354 \pm 0.0009$. Both components could be cool main-sequence stars. With the nuclear evolution of the components, the more massive one expands and probably experiences orbital shrinking owing to angular momentum loss. When the more massive star fills its Roche lobe, its matter flows through the $L_1$ into the Roche lobe of the less massive companion. At this time, the system becomes a semi-detached binary. The semi-detached configuration is hence probably the next stage of CSTAR 036162.
2. CSTAR 055495 is a semi-detached binary system with the unusual $q = 0.946 \pm 0.0006$, which indicates that CSTAR 055495 may be a rare binary system with the mass ratio close to one and the secondary component filling its Roche lobe. This means that a mass-ratio reversal just occurred, and CSTAR 055495 might be at a key evolutionary stage just after the mass-ratio reversal stage.
3. CSTAR 057775 is an A-type contact binary with $q = 0.301 \pm 0.0008$ and fill-out factor of $f = 0.742(8)$. The geometrical configuration of CSTAR 057775 suggests that it is a short-period binary in which both components are in contact with each other and share a common convective envelope.

Our results suggest that continuous photometric observations in multiple bands from Dome A of Antarctica, together with follow-up spectroscopic observations, can help to obtain detailed photometric solutions of different types of eclipsing binaries, and hence shed light on our understandings of binary systems.

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*Facilities:* DOME A: CSTAR, ATT (WiFeS), Magellan: Baade (Magellan Echellette Spectrograph).

*Software:* IRAF (Tody 1986, 1993), DAOPHOT: IRAF (Stetson 1987), PyWiFeS (Dopita et al. 2010, 2007), mtools: IRAF, UlySS (Koleva et al. 2009), W–D code 2013 version (Wilson 1971, 1979, 1990, 2012).

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